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Characterizing the Ballistic Performance of Polystyrene Foam for the Development of Body Armor Mannequin

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14. ABSTRACT
The Survivability/Lethality Analysis Directorate's Warfighter Survivability Branch designed a new ballistic mannequin for use in live-fire testing, constructed from 3/4-inch-thick plywood and rigid polystyrene foam. The objective of this test program was to construct an algorithm that uses fragment properties and depth of penetration in foam/plywood to estimate a striking velocity. To determine the effects of the foam and plywood combination on the velocity retardation of penetrators, we shot five threats (2-, 4-, 16-, 64-, and 207-gr right circular cylinders) at seven different foam and foam–plywood targets. From these data, we developed a two-factor power function relating fragment properties and depth of penetration to striking velocity.

15. SUBJECT TERMS
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Contents

List of Figures

List of Tables

Acknowledgments

1. Introduction

The Survivability/Lethality Analysis Directorate's Warfighter Survivability Branch designed a new ballistic mannequin (Fig. 1) for use in live-fire testing, constructed out of a single layer of 7-ply, 3/4-inch-thick AB marine-grade Douglas fir plywood sandwiched within rigid polystyrene foam. This mannequin is designed specifically for evaluating body armor systems in tests with fragmenting munitions. The design of the mannequin provides anatomical landmarks to support proper and consistent fit of body armor systems and sufficient geometric information to analyze penetration events that interrogate the body armor system and mannequin. The purpose of the plywood in the mannequin is to function as a witness panel for fragments that perforate the body armor system while the foam construction provides the required space claim to represent a 50th-percentile humanoid surface for equipping the body armor system. The mannequin shown in Fig. 1 is intended for use when the threat is from the front or the back. Similar mannequins with the plywood running front to back along the center of the mannequin can be used when the threat is from either side.
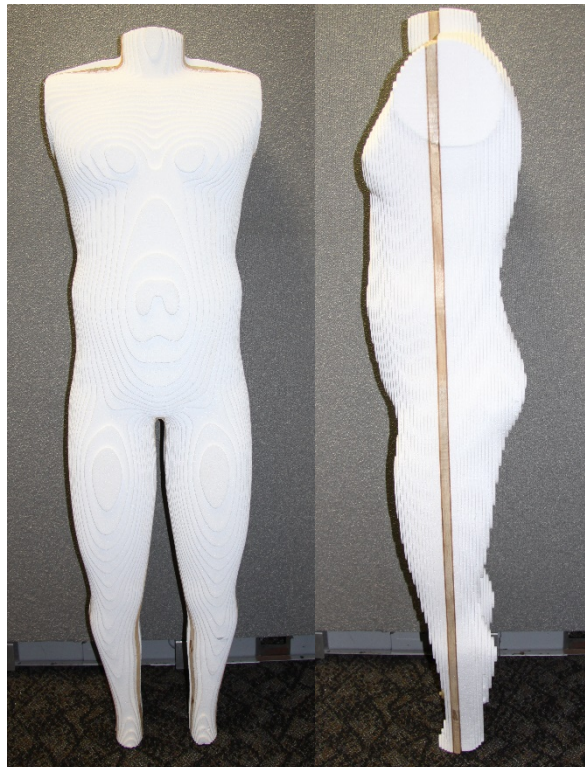
Fig. 1   Foam–plywood mannequin. Front view (L) and side view (R). The sandwich structure can be seen clearly in the side view.

2. Objective

The objective of this test program was to construct an algorithm that uses fragment properties and depth of penetration in polystyrene foam/plywood to estimate a striking velocity. To support this algorithm construction, we collected the ballistic penetration data of fragments into rigid polystyrene foam, plywood, and foam–plywood combinations.

3. Methods

To determine the effects of the foam and the foam–plywood combination on the velocity retardation of penetrators, we shot multiple threats at foam, plywood, and foam–plywood targets (Fig. 2).

Fig. 2   Target setup for shots on plywood (left, postshot), 3-inch foam only (center, preshot), and 6-inch foam–plywood combination (right, postshot)

3.1 Threats

Five different mass (2, 4, 16, 64, and 207 gr) threats were used, representing the four common fragments used for body armor ballistic testing and one larger threat near the upper bound of typical fragment distribution. All threats were steel right circular cylinders (RCCs) with a length-to-diameter ratio of approximately 1.

3.2 Targets

Seven different targets were used. Three were pure foam (0.875, 2.875, and 5.875 inches thick), one was plywood (3/4-inch marine grade), and three were foam glued to plywood (0.875-, 2.875-, and 5.875-inch-thick foam glued onto 3/4-inch marine-grade plywood). All targets were 8 × 8 inches in height and width. The foam used was 3 lb/ft^3 expanded polystyrene (Universal Foam Products, Hunt Valley, Maryland). The targets were held in place using a metal frame and straps (Fig. 2).

3.3 Calculated Quantities

The primary goal of this work was to determine velocity retardation equations for the foam and foam–plywood composite, relating depth of penetration in foam and/or plywood and threat characteristics to striking velocity. Secondary goals included determining how combined V50 values compared to individual V50 values (V50 foam/plywood = ? V50 foam + V50 plywood).

3.4 Definitions

- Complete Penetration: A complete penetration is any portion of the threat that perforates and completely exits the target. If the threat remains in the target, it is not a complete penetration.

- Partial Penetration: Any impact that is not a complete penetration is considered a partial penetration.

- Depth of Penetration: The measured length of the penetration into the target for partial penetrations.

3.5 Fair Hit Criteria

Each test shot shall be considered a fair hit if

- the shot-to-edge distance is no closer than 2 inches (50.8 mm),

- there is only one shot per target, and

- for fragments greater than 4 gr, the impact yaw is less than 5°.

4. Results

A total of 769 test shots were conducted across all seven targets, including shots removed due to exceeding the yaw limit (5° for the 16-, 64-, and 207-gr threat). Analysis was conducted both with and without the yaw-exceeding shots, with minimal difference between the two cases; therefore, results include the yaw-exceeding data.

4.1 V50

V50 values were calculated for each threat–target combination using a modified version of the Langlie sequential firing procedure to obtain the desired velocities (see the Appendix for more details on the procedure) for the first 10 shots (5 complete penetrations and 5 partial penetrations). As can be seen from the results

(Table 1), V50 values stack reasonably additively (e.g., V50 for 2.875-inch foam + V50 for plywood is close to the V50 for 2.875-inch foam glued to plywood).

Table 1   V50 values (ft/s) for each target–threat combination

Target	Foam thickness (inches)	Plywood thickness (inches)	2-gr threat V50	4-gr threat V50	16-gr threat V50	64-gr threat V50	207-gr threat V50
A	5.875	0.75	2303.7	1814.4	1205.5	820.21	612.02
B	2.875	0.75	1966.4	1621.6	1079.6	751.61	488.70
C	0.875	0.75	1772.2	1401.9	947.88	676.96	401.98
D	5.875	N/A	825.54	771.12	571.71	425.47	297.41
E	2.875	N/A	565.56	527.08	404.36	263.36	177.12
F	0.875	N/A	263.06	276.50	180.95	102.38	69.504
G	N/A	0.75	1585.7	1305.3	790.25	538.44	341.12

4.2 Depth of Penetration vs. Striking Velocity

Equations relating depth of penetration to striking velocity were then calculated. As current plywood penetration equations (Bruchey 1975) have a power function relating striking velocity to Ax/m (threat presented area * depth of penetration / threat mass), a two-factor power function was used to fit the data:

$$V_s = c_1 * \left(\frac{Ax_1}{m}\right)^{c_2} + c_3 * \left(\frac{Ax_2}{m}\right)^{c_4},$$

where A = presented area of threat (inches^2), x_1 = depth in foam (inches), x_2 = depth in plywood (inches), m = mass of threat (gr), $c_1 - c_4$ = best fit coefficients. The coefficients that best fit the data are shown in Table 2 and the resultant surface in Fig. 3. Note that these coefficients are when using inches, grains, and feet per second for depth, mass, and velocity. Values for c_1 and c_3 will be different for metric units (see Conclusions for values).

Table 2   Coefficients determined

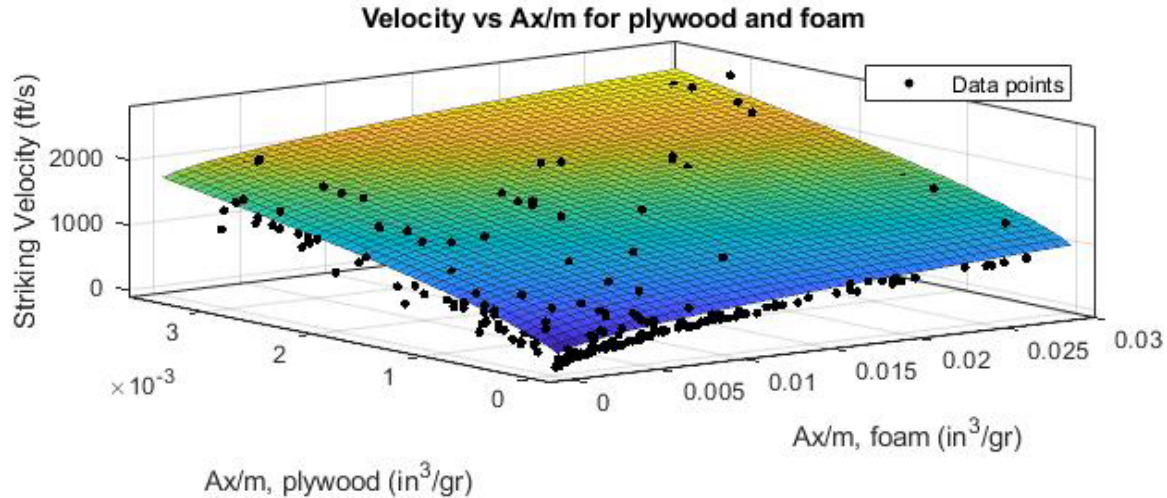|	
c_1	4438
c_2	0.4802
c_3	64800
c_4	0.6669

Fig. 3   Striking velocity vs. Ax/m for foam and plywood

5.   Discussion

5.1 V50

In all cases, the combined V50 (V50 plywood + V50 foam) was close to the measured V50 of the combined foam and plywood (Table 3). The largest difference was 17.5% for the 64-gr threat against 5.875-inch foam, and the smallest was 2.2% for the 207-gr threat against the 0.875-inch foam. So although the V50s stack reasonably well, it is best to test on the combined foam–plywood than to combine individual values for foam and for plywood.

Table 3   Percent difference between combined V50 and measured V50 for five threat sizes against three different foam thicknesses

Foam thickness (inches)	Threat size				
	2 gr	4 gr	16 gr	64 gr	207 gr
0.875	–4.67%	–14.44%	–12.98%	–17.52%	–4.33%
2.875	–9.4%	–13.00%	–10.65%	–6.68%	–6.04%
5.875	–4.32%	–12.83%	–2.46%	5.34%	–2.15%

For all but one case (64-gr threat against 0.875-inch foam), combined V50 was less than measured V50. This is to be expected since more energy is required to cause blowout (larger exit hole) in pure foam than to cause the clean exit hole in foam when there is plywood behind it.

Compared to previous work, our V50s are close to those measured by others. Kaufman and Moss measured values between 768 and 928 ft/s for a 16-gr sphere

for varying types of 3/4-inch plywood (2015). This is similar to our measurement of 790.25 ft/s for a 16-gr RCC. Also, since an RCC has a smaller presented area than a sphere, a value on the lower side is to be expected. Further, Kaufman and Moss estimated the V50 for a 16-gr sphere from the data used in Bruchey (1975) and calculated a value of 813 ft/s, again similar to our value. As no previous work has been done with V50 in expanded polystyrene foam, comparisons cannot be made.

5.2 Depth of Penetration vs. Striking Velocity

The two-factor power function best fit curve (Fig. 3) fits the data well (adjusted R-square value of 0.941 and root mean square error of 132.8). Data fit better in the middle area (combined foam and plywood) than at the near edges (pure foam or pure plywood). As these data will be used in mannequins of combined foam and plywood, the values in the middle area are more important than those along the edges.

5.3 Foam Consistency

To verify the consistency of the foam response, we first calculated the density of each pure-foam target to determine sheet to sheet variation since different targets were cut from different sheets of purchased foam. The average density of the pure foam blocks was 2.95 ± 0.22 lb/ft^3 (nominal density of 3 lb/ft^3). Further, we plotted striking velocity versus Ax/m, just as in Fig. 3, but focused on only the pure foam targets (Fig. 4). From the tight confidence interval in Fig. 4, we can see that even when there is some variation in target density, the effect on foam response is minimal.
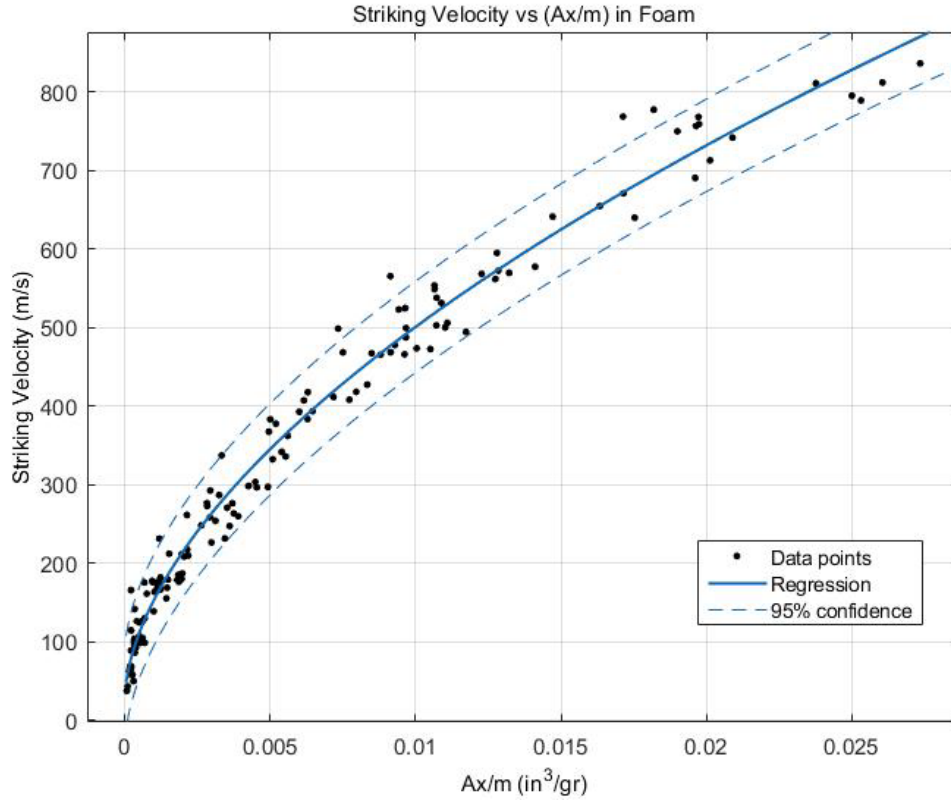
Fig. 4   Striking velocity vs. Ax/m for pure foam targets with 95% confidence interval

6.   Conclusions

We conducted tests on pure foam and pure plywood and combined foam–plywood targets to determine velocity retardation equations for penetrating fragments.

$$V_s = 4438 * \left(\frac{Ax_1}{m}\right)^{0.4802} + 64800 * \left(\frac{Ax_2}{m}\right)^{0.6669} ,$$

where A = presented area of threat (in^2), x_1 = depth in foam (inches), x_2 = depth in plywood (inches), and m = mass of threat (gr). If, however, units are changed to centimeters, grams, and meters per second, the coefficients would change to the following:

$$V_s = 94.91 * \left(\frac{Ax_1}{m}\right)^{0.4802} + 493.1 * \left(\frac{Ax_2}{m}\right)^{0.6669} ,$$

where A = presented area of threat (cm^2), x_1 = depth in foam (cm), x_2 = depth in plywood (cm), and m = mass of threat (g). These equations can be used to calculate striking velocity when fragment parameters and depth of penetration are known from live fire tests.

7.   References

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Kaufman MB, Moss LLC. Reassessing the representative heuristic of the plywood ballistic mannequin used in life-fire testing. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2015 April. Report No.: ARL-TR-7274.

Appendix. A Modified Langlie Sequential Firing Procedure[*]

The sequential firing procedure based on the Langlie method (DARCOM Pamphlet 706-103, 1983 and TOP 2-2-710) was conducted to select velocities for obtaining estimates of the $v50$ ballistic limit. Several modifications were made to obtain velocities away from the mean to better estimate the entire response curve, and to establish stopping rules.

1. Select lower and upper projectile velocity limits (gates) for the threat tested. The lower gate is that velocity where we would expect to consistently see partial penetration. The upper gate is that velocity where we expect to consistently see complete penetration. These gates should be set so that lower gate is at least 20 m/s lower than the lower limit of the expected zone of mixed results and the upper gate is at least 20 m/s higher than the upper limit of the expected zone of mixed results.

2. Fire the first round at a velocity midway between these two limits.

3. If the first round results in a complete penetration, drop the velocity of the second round halfway between the first round velocity and the lower limit velocity; if the first round results in a partial penetration, raise the velocity of the second round to halfway between the first round velocity and the upper limit velocity.

4. If the first two rounds result in a reversal (one partial, one complete), fire the third round midway in velocity between the velocity of the first two rounds. If the first two rounds result in two partials, fire the third round at a velocity half way between the second round and the upper limit. If the first two rounds result in two complete penetrations, fire the third round at a velocity half way between the velocity of the second round and the lower limit.

5. If a reversal does not occur in three rounds adjust the lower and upper limits as follows. If all rounds resulted in partials, raise the lower and upper limits by 20 m/s and fire the next round halfway between the last round and the new upper limit. If all rounds resulted in complete penetrations, decrease the lower and upper limits by 20 m/s. Fire the next round half way between the last round and fire the next round halfway between the last round and the new lower limit.

6. Fire the succeeding rounds as follows;

   a. If the preceding PAIR of rounds resulted in a reversal, fire at a velocity midway between the two velocities.

   b. If the last two rounds did not produce a reversal look at the last four rounds. If the number of completes and partials is equal, fire the next

round between the velocity of the first and last round of the group. If the last four did not produce equal numbers of partials and completes, look at the last six, eight, …, until the number of partials and completes is equal. Always fire at a velocity that is half way between the first and the last round of the group examined (not necessarily the highest and lowest of the group).

c. If the conditions in 6b above cannot be satisfied and the last round resulted in a complete, fire the next round at a velocity midway between the last round and the lower velocity limit, or if the last round resulted in a partial, fire at a velocity midway between the last round and the upper velocity limit.

d. Continue as in 6a and 6b above for a minimum of 10 shots and a maximum of 15 (for this firing program) until the following stopping rules can be applied:

i. Obtain a zone of mixed results (at least one partial penetration has a higher velocity than a complete penetration). The size of the zone of mixed results is defined as the difference in velocity between the highest partial penetration and the lowest complete penetration.

ii. The average of the complete penetrations is larger than the average of the partial penetrations.

iii. The spread of the tightest (smallest velocity spread among all shots) three partial penetrations and the three complete penetrations is within 38 m/s (125 ft/s).

iv. Ensure that the data set contains values approximately $\pm 1 \Delta$ from the V_{50} that is estimated from the tightest three partial penetrations and three complete penetrations. Set Δ to ± 20 m/s unless a wider band is required as given in step 5. (This value does not have to be the same as the gate radius). If velocities do not exist at these outer values, test at a velocity of $V_{50} + \Delta$ m/s and/or $V_{50} - \Delta$ m/s. Where shots permit, (assuming the previous data were properly obtained with less than 10 shots) an additional shot(s) may be conducted at the following velocities to provide more balanced data:

• between the lowest shot (the aforementioned $V_{50} - \Delta$) and the lowest complete penetration

• between $V50 + \Delta$ and the highest partial penetration.

Use all data to get estimates of the V_{50} using maximum likelihood estimation or general linear models.

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List of Symbols, Abbreviations, and Acronyms

ARL   US Army Research Laboratory

RCC   right circular cylinder

WMRD   Weapons and Materials Research Directorate

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